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16. Abstract

A delayed flap approach procedure developed by NASA-Ames was flight tested using the NASA CV-990 airplane to measure and analyze the noise produced beneath the flight path. Three other types of landing approaches were also flight tested to provide a comparison of the noise reduction benefits to the delayed flap approach. The conventional type of approach was used as a baseline to compare the effectiveness of the other approaches. The reduced flap approach used represents an ATA recommended procedure for reducing landing approach noise. The decelerating approach is a variation of the delayed flap approach.

A detailed comparison of the ground-perceived noise generated during the approaches is presented. For this comparison, the measured noise data were normalized to compensate for variations in aircraft weight and winds that occurred during the flight tests. The data show that the reduced flap approach offers some noise reduction, while the delayed flap and decelerating approaches offer significant noise reductions over the conventional approach.

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SUMMARY

A delayed flap approach procedure developed by NASA-Ames was flight tested using the NASA CV-990 airplane to measure and analyze the noise produced beneath the flight path. Three other types of landing approaches were also flight tested to provide a comparison of the noise reduction benefits to the delayed flap approach. The conventional type of approach was used as a baseline to compare the effectiveness of the other approaches. The reduced flap approach used represents an ATA recommended procedure for reducing landing approach noise. The decelerating approach is a variation of the delayed flap approach.

A detailed comparison of the ground-perceived noise generated during the approaches is presented, For this comparison, the measured noise data were normalized to compensate for variations in aircraft weight and winds that occurred during the flight tests. The data show that the reduced flap approach offers some noise reduction, while the delayed flap and decelerating approaches offer significant noise reductions over the conventional approach.

INTRODUCTION

Since aircraft noise became a major problem to communities around airports, several successful remedies have been used by the air transportation industry to reduce the noise impact. Technological solutions involving engine design have been used to reduce the noise level of the new wide-body jet transports. Engineering solutions involving changes in operational procedures have been used for the older transports that have not been equipped with quiet engines. Changes such as raising the ILS glide slope capture altitude provide noise reduction at distances greater than 13 to 19 km (7 to 10 n.mi.) from the airport. Further noise reductions closer to the airport have been obtained with a "reduced flap" approach, in which the aircraft is flown with one notch less than minimum landing flaps down the ILS approach path to an altitude of 300 m (1000 ft) where the minimum certified landing flap is selected for the final approach.

In an attempt to achieve further reductions in noise through refinements in operational procedures, NASA-Ames Research Center has developed a "delayed flap" approach which uses an energy management approach and minimizes the noise by keeping the aircraft in a clean configuration late into the approach and decelerating at low power settings. In this approach, the aircraft is stabilized on the final approach speed and in the landing configuration at an altitude of 150 m (500 ft). Preliminary simulation studies indicated that this type of approach could reduce the landing approach noise area to about 40 percent of that of the conventional approach (ref. 1). Since these simulation results were promising, ARC implemented an energy management system for the delayed flap approach concept on an airborne digital autopilot computer in NASA's CV-990 jet transport and conducted a flight test to determine the noise benefit.

A series of flights were conducted at Edwards Air Force Base in September 1975 to measure the ground-perceived noise of the CV-990 airplane during conventional ILS, reduced flap, delayed flap, and decelerating types of landing approaches. Dryden Flight Research Center conducted the noise measurement aspect of the tests and provided the final noise data to ARC.

The flight test data were generalized to provide a more meaningful comparison of the noise reduction benefits. The test site was not typical of many ILS runways since the glide slope is 2.5° instead of the usual 3°. Additionally, the aircraft weight varied significantly and there were variable winds at altitude during the tests. Consequently, the measured data was corrected to correspond to an airplane weight of 81,500 kg (180,000 lb) — a typical heavy landing weight — a sea level runway with no wind disturbances, and a 3° ILS glide slope. This was accomplished subsequent to the flight test, using a simulation of the CV-990 airplane. The simulation included engine and noise models which were adjusted so that simulated approach noise agreed with the flight test approach noise. The airplane and noise models were then used to generate the ground-perceived noise for the four different types of landing approaches.

The purpose of this report is to describe the test and procedures used and to present a detailed comparison of the ground-perceived noise generated during the four types of landing approaches. A comparison of the fuel consumption of the four approaches as well as the applicability of the energy management approaches to other airline aircraft are presented in reference 2.

TEST AIRCRAFT

The NASA CV-990 airplane used for these tests is a swept-wing, 4-engine, jet transport similar in performance to most other present-day jet transports (fig. 1). It is powered by four General Electric CJ-805-23B axial flow aft-fan turbojet engines, delivering a maximum thrust of 71,400 N (16,050 lb) each. The maximum takeoff weight is 114,800 kg (253,000 lb) and the maximum landin. weight is 90,720 kg (200,000 lb). The wings are equipped with full-span Kr...er flaps on the leading edge and with partial-span, double-slotted

Fowler flaps on the trailing edge. Ten and twenty-seven degrees of flap are normally used for the takeoff and landing approach phases of flight. Thirty-six and fifty degrees of flap are the certified landing flap settings, with fifty degrees being the normal setting.

The aircraft is equipped with the Digital Avionics System (DAS), which is an integrated flight director/autopilot system. The DAS provides all of the conventional autopilot modes as well as an autoland capability. Additionally, the DAS performs the energy management computations and provides the commands to the pilot that are necessary for flying the delayed flap approach in a consistent manner. This consistency is necessary to provide the delayed flap approach noise benefits that will be discussed later. A functional description of the DAS is given in reference 3.

INSTRUMENTATION AND DATA REDUCTION

The noise measurement system consists of an array of 1-in. and 1/2-in. condenser microphones with cathode followers and power supplies and recording equipment housed in a mobile van. Figure 2 shows one of the microphone stations and the van. The microphone signals are routed through shielded 2-conductor cables to a 14-track wideband FM tape recorder housed in the van. Voice comments and a broadcast time code are also recorded on the tape. The system is capable of measuring and recording noise from 24 microphones.

For the flight tests, the microphone stations were deployed along the aircraft approach path to runway 22 at Edwards AFB as shown in figure 3. The station locations are on Rogers Dry Lake which has a hard clay surface. At each location under the approach path, two tripod-mounted microphones were used. One tripod-mounted microphone was used at each sideline station. Before and after each day's flight test, an acoustic calibration was applied to each microphone. The resulting signal was recorded for later use in the data reduction process.

The noise data reduction process included a 1/3 octave band spectral analysis of the noise recordings by a computer-controlled real-time analyzer. The analyzer meets the FAR part 36 specifications (ref. 4) for equipment used to analyze noise data. The data were scaled, frequency corrections were made where required, and the data were corrected to standard-day conditions using the procedure described in reference 3. The noise measured by the tripod-mounted microphones included ground reflection effects (ref. 5).

The airplane position during the landing approaches was measured by a tracking radar adjacent to the test site. A C-band radar transponder was installed in the airplane to aid the radar tracking. The radar data were recorded with a broadcast time code to correlate the noise measurements with the airplane position. After the flight tests, the radar data were smoothed and processed to obtain airplane position relative to the runway.

Airborne data was collected on the Airborne Digital Data Acquisition System (ADDAS) installed in the passenger section of the CV-990. The ADDAS consists of a general-purpose digital computer with line printer and magnetic tape outputs and analog-to-digital input interfaces. It collects analog data from the aircraft control surface transducers and the Engine Parameter Measurement System (EPMS) and digital data from the Inertial Navigation System (INS), Digital Avionics System (DAS), and the Time Code Generator; it stores these data on magnetic tape for postflight processing. A detailed description of the ADDAS is given in reference 6. The EPMS is an interface unit that connects the aircraft engine instrumentation (tachometer (RPM), pressure ratio (EPR), exhaust gas temperature (EGT), and fuel flow) to the ADDAS and provides a complete set of performance data for each engine. These data were used to check the aircraft simulation engine model.

FLIGHT TEST PROCEDURE

The flight tests were flown on days when the relative humidity was greater than 30 percent, there was little or no atmospheric turbulence, and the surface winds were less than 10 knots as required in reference 4. These conditions were satisfied so that the noise measurements would not be adversely affected.

Four types of landing approaches were flown. A minimum of four data runs for each type of landing approach was made to obtain the test data. In each approach the pilot, using the onboard DAS guidance and navigation functions, set up the aircraft to intercept the ILS localizer at a distance of 28 km (15 n.mi.) from touchdown, at an altitude of 914 m (3000 ft) above ground, in a clean configuration at 240 knots indicated airspeed (IAS). The aircraft then flew an automatic, coupled ILS approach, capturing the glide slope at 20.9 km (11.3 n.mi.) from touchdown at an altitude of 914 m (3000 ft). The aircraft tracked the glide slope down to a height of about 20 m (66 ft) and then executed an auto-flare touchdown. The various approaches were flown along the same ILS approach geometry and differed only in the airspeed profile and configuration schedule.

The first approach type was the "conventional" or standard ILS approach. Starting at 28 km (15 n.mi.) from touchdown, power is reduced to idle and the aircraft slows to 180 knots IAS as shown in figure 4. Ten degrees of flap are selected and the power is set to maintain 180 knots IAS. At glide-slope capture, 27° of flap are selected and the aircraft is slowed to V_{ref} plus 10 knots. This condition is maintained until the aircraft reaches the outer marker, 13 km (7 n.mi.) from touchdown, where 50° of flap are selected, the landing gears are lowered, and the speed is reduced to V_{ref} plus 5 knots. This airspeed is maintained for the remainder of the approach.

The second approach type, the "reduced flap" approach, is an Air Transport Association (ATA) recommended procedure for reducing landing approach noise. This approach is identical to the conventional approach described above until the aircraft reaches the outer marker. At this point, the landing

gear is lowered, but the airspeed is maintained at V_{ref} plus 10 knots and the flaps are left at 27° (see fig. 4). At 305 m (1000 ft) above ground, 7.0 km (3.8 n.mi.) from touchdown, 36° of flap are selected and the aircraft is slowed to V_{ref} plus 5 knots. By maintaining the 27° flap condition longer and then using the minimum landing flap setting, this approach achieves a noise saving over the conventional approach through the lower required power settings.

The "delayed flap" approach, the third approach type, is a decelerating airspeed approach in which the aircraft is stabilized in the final approach configuration at 150 m (500 ft) above the ground. The aircraft captures the glide slope in a clean configuration at 240 knots IAS. In response to commands given by the DAS computer, the pilot sets the throttles to idle at 10.2 km (5.5 n.mi.) from touchdown. The landing gear is commanded down at 10.0 km (5.4 n.mi.). The 10° flap command is given at 9.1 km (4.9 n.mi.) and the landing flap (36°) command is given at 6.9 km (3.7 n.mi.). When the airspeed delays to within 15 knots of V_{ref}, an approach power command is given and the pilot applies power to stabilize the airspeed at V_{ref} +5. The aircraft is then in the landing configuration at V_{ref} +5 when it reaches the 150 m (500 ft) altitude point. These configuration changes occur at different points depending upon the ILS glide-slope angle, the wind along the approach, and the aircraft weight.

The fourth approach type, the "decelerating" approach, is identical to the delayed flap approach except that the deceleration continues to touchdown. Hence, the power remains at idle throughout the approach. The airspeed and configuration profile is similar to the profile for the delayed flap, with the speed curve and configuration changes moved 3.5 km (1.9 n.mi.) closer to the touchdown point.

NOISE MODEL DEVELOPMENT

The model of the ground-perceived noise generated by the CV-990 airplane was developed empirically to predict approach-to-landing aircraft noise. The perceived propulsive and airframe noise components were modeled separately and the total noise was computed by logarithmically summing these two components. A description of the noise model is given in the appendix.

In essence, the noise model parameters were adjusted so that the predicted noise matched the flight test measurements. Since the predominant noise generated during a stabilized approach is from the aircraft engines, the propulsive noise model was adjusted by matching the flight test data from the conventional and reduced flap approaches, which have high thrust levels. The airframe noise model parameters were adjusted using the noise measurements from the decelerating approach, since the airspeed is high and the thrust levels are low throughout this type of approach.

Data taken from an earlier flight test, reported in reference 7, also provided information on the propulsive noise at low power settings.

Reference 8 shows that for airspeeds above 160 knots, airframe noise is dominant for the CV-990 at idle thrust in the landing configuration. During the decelerating approach, the airspeed is above 160 knots until the aircraft is within 1 km (0.5 n.mi.) from touchdown.

RESULTS AND DISCUSSION

Noise Model Verification

Simulated landing approaches of each type of approach were made to assess the accuracy of the aircraft noise model. In each case the flight test wind profile, as measured by the aircraft INS, was simulated and the average flight test weight for each approach type was used. Figure 5 shows the measured and calculated centerline effective perceived noise level (EPNL) generated by the CV-990 on each of the four approaches. The curve in the figure is the noise calculated by the computer noise model. The vertical bars are the range of flight test noise data that was measured on four landing approaches of each approach type.

Figure 6 shows the measured and calculated sideline EPNL at distances of 1.9 km (1 n.mi.) and 5.6 km (3 n.mi.) from touchdown for the conventional and decelerating approaches, respectively. The curves in the figure are the noise profiles computed using the noise model; the vertical bars are the range of flight test data.

From the comparison of the flight test noise measurements to the computed noise, it is apparent that the noise model accurately predicts the landing approach noise for conditions similar to the flight test conditions. However, there are limitations on the applicability of the model due to the lack of additional verification data. The accuracy of the airframe noise model diminishes for airplane altitude greater than 346 m (1194 ft) AGL, since this is the maximum altitude for which noise was measured while the engines were at idle. Similarly, the accuracy of the propulsive noise model diminishes for airplane altitudes greater than 610 m (2000 ft).

Generalized Noise Comparison

With the aircraft noise model modified by the flight test noise measurements, the flight test results were generalized by simulating the four approach types using a 3° glide slope at a sea level runway. In addition, all approaches were made with an airplane weight of 81,500 kg (180,000 lb). The initial conditions for each approach were the same as those described in the flight procedures section.

Figure 7 shows the centerline noise profile for all four approach types in a no-wind condition. Note that the conventional and reduced flap approaches are identical until the outer marker is reached (13 km (7 n.mi.)). At this point, recall from figure 4 that in the conventional approach, the

landing gear is extended, 50° flaps are selected, and the airplane is slowed to V_{ref} +5 knots; while in the reduced flap approach, the landing gear is extended, and the 27° flaps are maintained. The reduced flap approach derives its noise reduction benefit from delaying the landing flap extension until an altitude of 305 m (1000 ft) above ground level is reached. This occurs 5.7 km (3.1 n.mi.) from touchdown, where a landing flap setting is selected that is one notch less than the normal setting (i.e., 36° for the CV-990).

In the delayed flap and decelerating approaches, the distances at which the configuration changes are made change as a function of winds, aircraft weight, and ILS glide-slope angle. For both the delayed flap and decelerating approaches, the throttles are set to idle at glide-slope capture and retained there throughout most of the approach. The data show that there is a significant reduction in the noise lev 's over either the conventional or reduced flap approach.

All four approaches were also simulated in the presence of headwinds. The wind model, described in reference 1, has a speed profile shown in figure 8, which represents a 3-sigma case. Figure 9 shows the centerline EPNL for the four approaches in the headwind condition. There was an increase of about 1 dB in noise for all of the approaches. Although the thrust increase caused by the headwind was the same for both the reduced flap and conventional approaches, the noise increase was greater for the reduced flap approach since the engines were operating in a region where the noise variation with thrust is greater than in the case of the conventional approach. Therefore, in a headwind, the noise difference between the conventional and reduced flap approaches is insignificant compared to the scatter in the flight test noise measurements.

Figure 10 shows the 95 dB, 90 dB, and 85 dB EPNL contour shapes for each type of approach on a 3° glide slope in a no-wind condition. The increase in the delayed flap approach area at 3.5 km (1.9 n.mi.) from touchdown corresponds to the point where power is applied to maintain the final approach airspeed. Recall from the description of the delayed flap approach that, from 150 m (500 ft) altitude down to touchdown, the aircraft configuration and airspeed is the same as in the reduced flap approach. Therefore, from about 3 km (1.6 n.mi.) to touchdown, the ground-perceived noise is the same as for the reduced flap approach.

A comparison of the 90 dB EPNL contour area is shown in figure 11. The areas have been normalized to the conventional approach area to show the relative sizes for the other approaches. The 90 dB contour areas for the decelerating and delayed flap approaches are 15 percent and 28 percent of the conventional approach area, while the reduced flap area is 91 percent of the conventional approach area. In terms of ground area affected, the decelerating and delayed flap approaches offer significant noise reductions over the conventional approach.

CONCLUSIONS

Four types of landing approaches were flight tested using the NASA CV-990 airplane to measure and analyze the noise produced beneath the flight path. The measured noise data was normalized to compensate for variations in aircraft weight and winds which occurred during the flight tests. As a result, the following conclusions can be made.

1. The delayed flap and decelerating approaches offer significant noise reductions over a conventional approach. The decelerating approach 90 EPNdB contour area is 15 percent, the delayed flap approach area is 28 percent, and the reduced flap approach area is 91 percent of the conventional area.

2. In the presence of headwinds, the difference between the centerline noise of the conventional approach and the reduced flap approach for the CV-990 is insignificant compared to the scatter in the flight test noise measurements.

APPENDIX

CV-990 NOISE MODEL

The CV-990 noise model is divided into a propulsive component and an airframe component. A description of the two components will be presented separately.

The form of the propulsive noise model was based on data presented in reference 9 which shows that the ground-perceived noise directly below the aircraft flightpath is a function of altitude and thrust. The altitude effect is approximately the same for different thrust levels. Consequently, the propulsive noise model was chosen to be a function of distance for one reference condition. A correction term was applied that is a function of thrust variation from the reference. Since the noise is computed in terms of effective perceived noise, which is a function of the noise duration, an additional correction term was added to compensate for true airspeed variation from the reference. The propulsive noise model in EPNdB is given by

$$E_p = N_{ref} + N_T + N_{py} - 10 \log_{10}(V_T/150)$$

N_{ref} is the reference noise level for an airplane condition of 150 knots true airspeed, 50° of flap, and landing gear down, and is given by

$$N_{ref} = 152.2 - 19.6 \log_{10} R$$

where R is the distance in meters from the airplane to the ground observer. N_T is the thrust variation correction term and is given by

$$N_T = \begin{cases} 13.5(T - 1) - 5.5 & , T < 1 \\ 12 \quad (T - 1.5)/1.5 - 1.5 & , 1 \leq T < 1.5 \\ 4.5(T - 2.25)/2.25 & , 1.5 \leq T \end{cases}$$

where T = (total thrust in nt)/44,800. N_{py} is the excess ground attenuation for noise propagation in a lateral direction, perpendicular to the airplane ground track. The several factors that affect sideline noise attenuation were combined into the excess ground attenuation since there were sufficient sideline noise measurements. N_{py} is given by

$$N_{py} = \begin{cases} 0 & , \quad y \leq 305 \text{ m} \\ -17 \log_{10}(y/305) & , \quad y > 305 \text{ m} \end{cases}$$

where y = lateral distance in meters from the airplane ground track to the ground observer.

The airframe noise model was based on the results given in reference 8. It was found that the airframe noise for the CV-990 was an inverse square function of distance. Since the propulsive noise approximately followed the same function of distance, the airframe noise was modeled as a constant level below the propulsive noise at the reference condition previously described. Correction terms are applied for variations from the reference condition. Hence, there are terms proportional to changes in the landing gear and flap positions. The division of the noise increments between flap and gear was based on the results given in reference 8, which indicated that the flaps produced the larger noise increment. Additionally, the airframe noise is known to be proportional to the aircraft true airspeed. From the results given in reference 8, the airframe effective perceived noise was selected to be proportional to the fifth power of true airspeed. The complete airframe noise model in EPNdB is given by

$$E_A = N_{ref} - 26.0 + 8.5\delta_F/50 + 2L_G + N_{Ay} - 50 \log_{10}(V_T/150)$$

where δ_F is the flap angle in degrees, L_G is the landing gear position (L_G = 1 when the gears are down), and V_T is the airplane true airspeed. N_{Ay} is the airframe noise excess ground attenuation model and is given by

$$N_{Ay} = \begin{cases} 0 & , \quad y \leq 305 \text{ m} \\ -4.16 \log_{10}(y/305) & , \quad y > 305 \text{ m} \end{cases}$$

where y is the lateral distance in meters from the airplane ground track to the ground observer.

The propulsive and airframe noise components are added logarithmically to give the total effective perceived noise

$$E = 10 \log_{10} 10^{E_P/10} + 10^{E_A/10}$$

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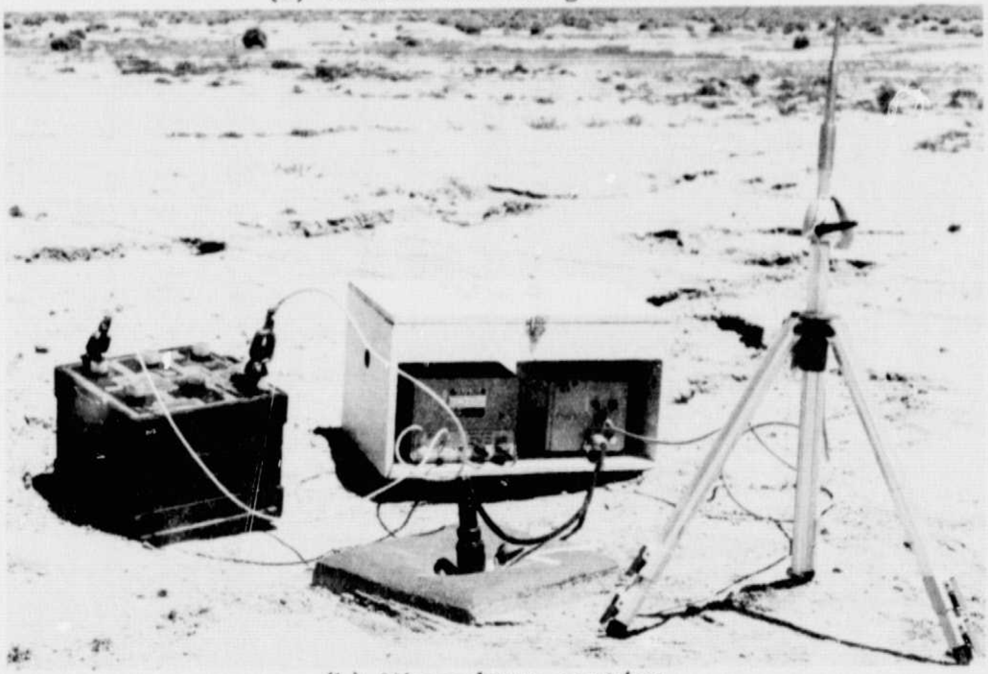
Figure 1.- CV-990 jet transport.

(a) Mobile van and generator.



(b) Microphone station.

Figure 2.- Noise measurement system components.

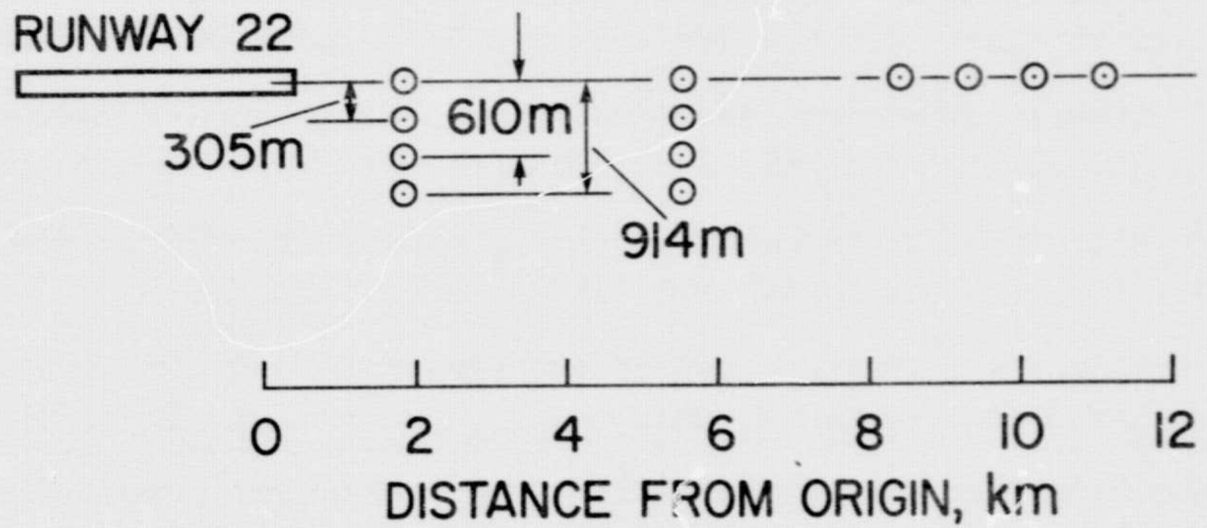


Figure 3.- Microphone array for delayed flap approach noise measurements.

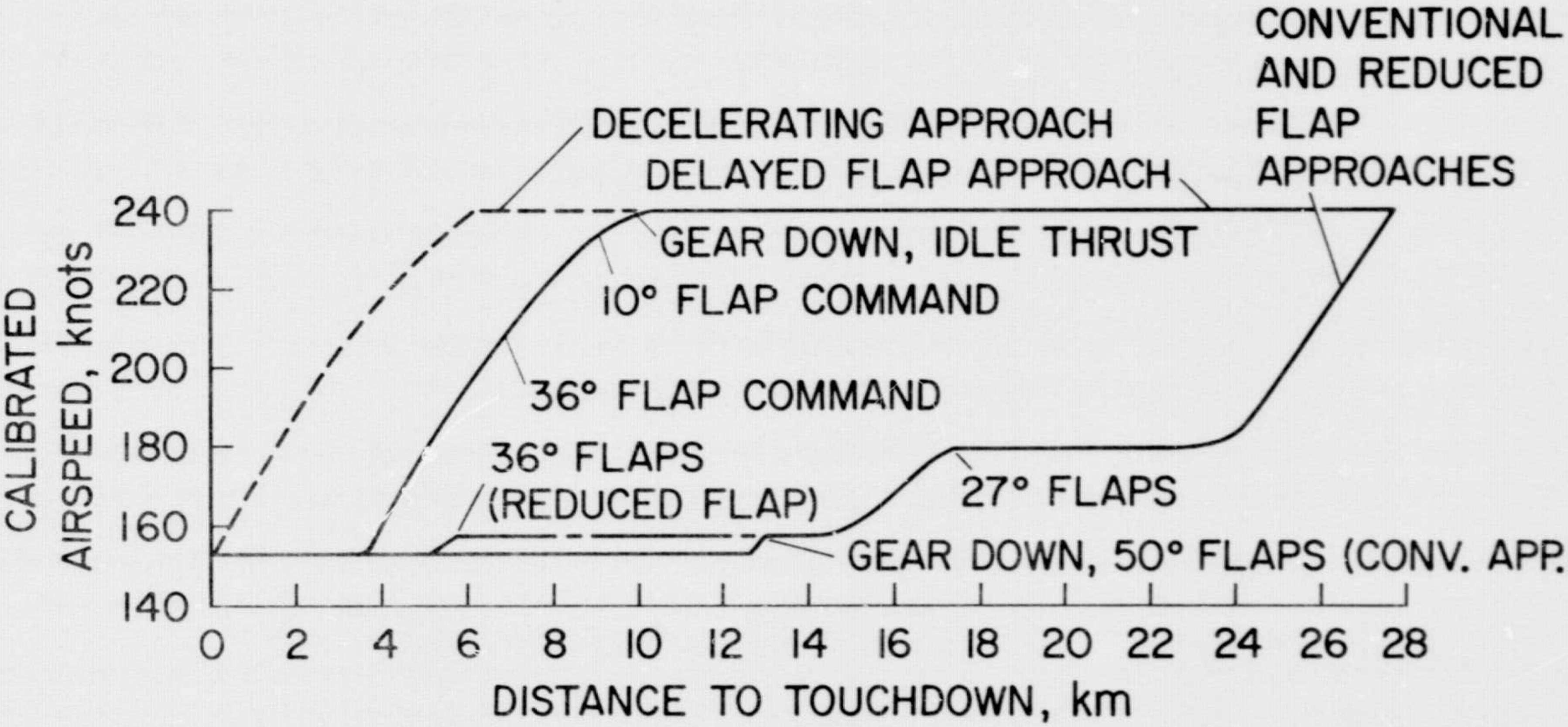
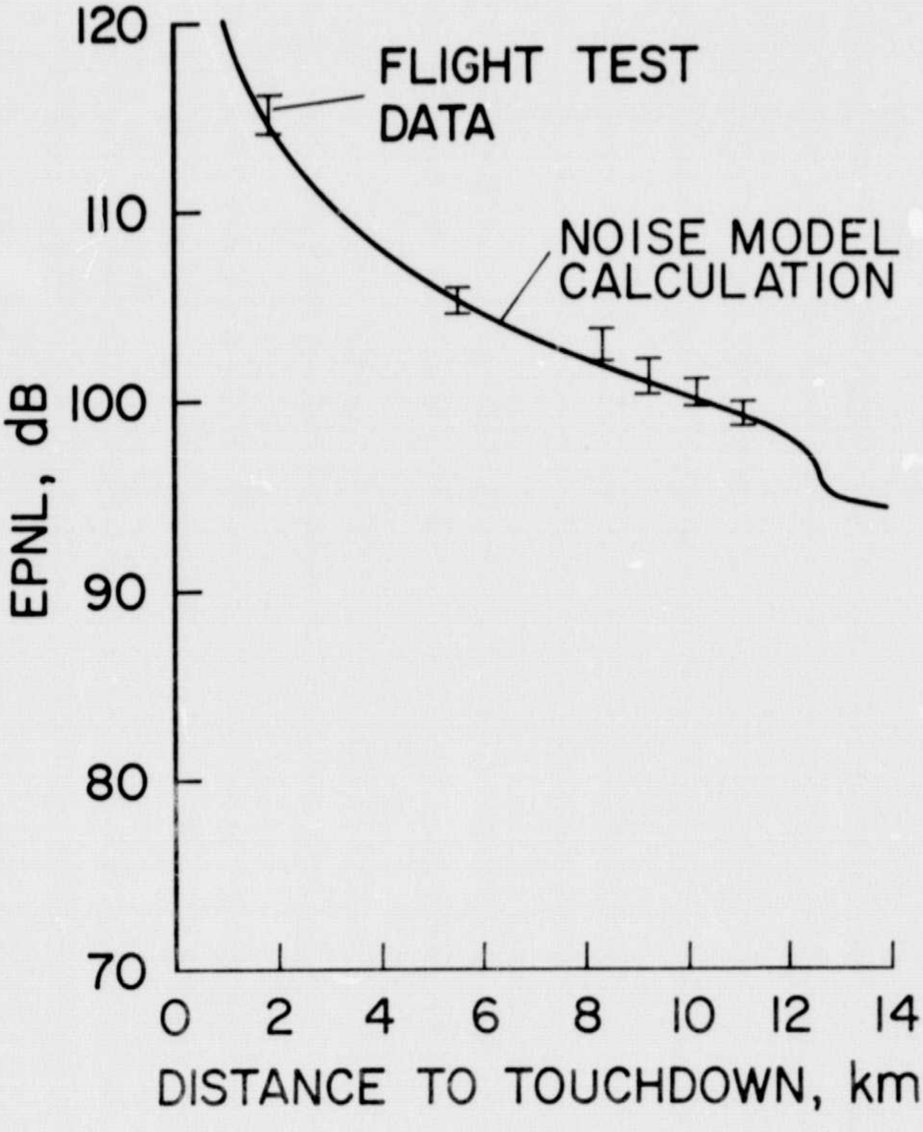
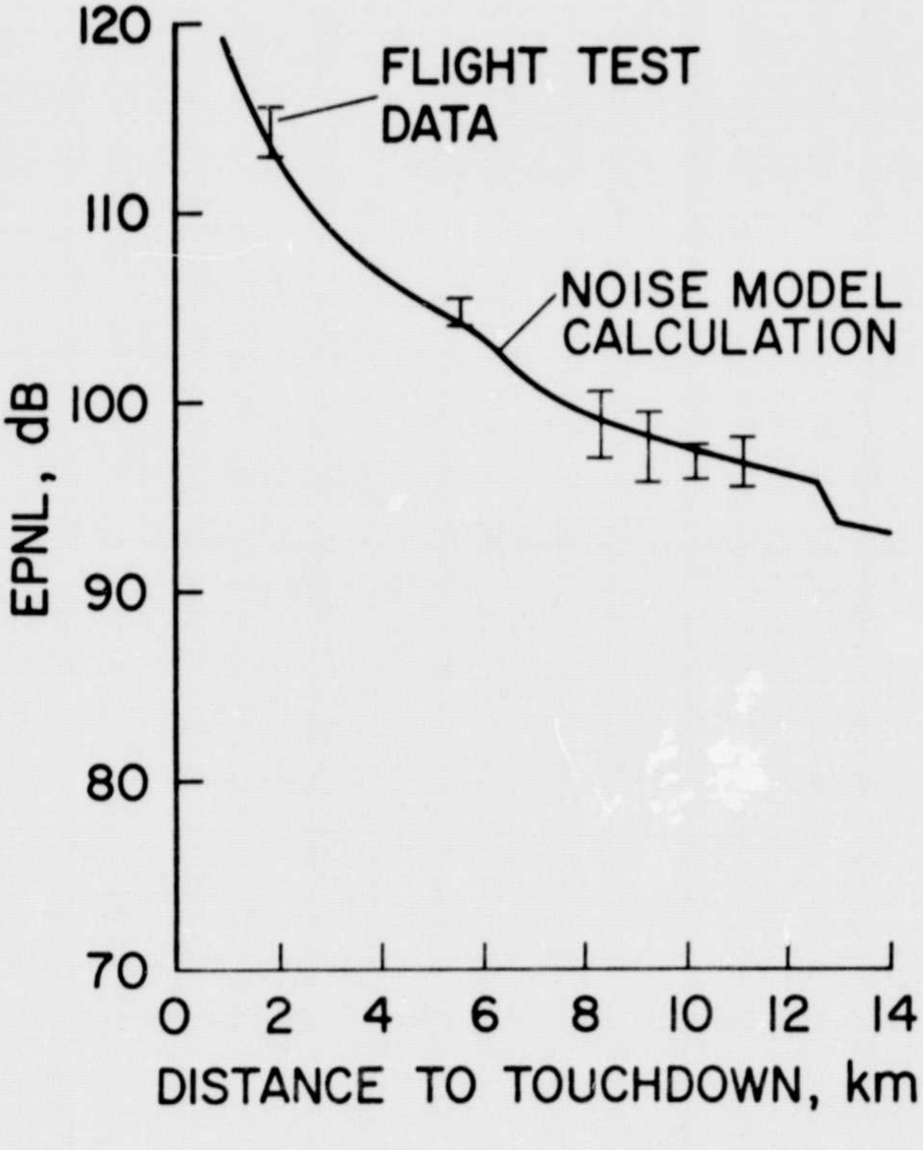


Figure 4.- Airspeed profiles for the flight-test approaches.



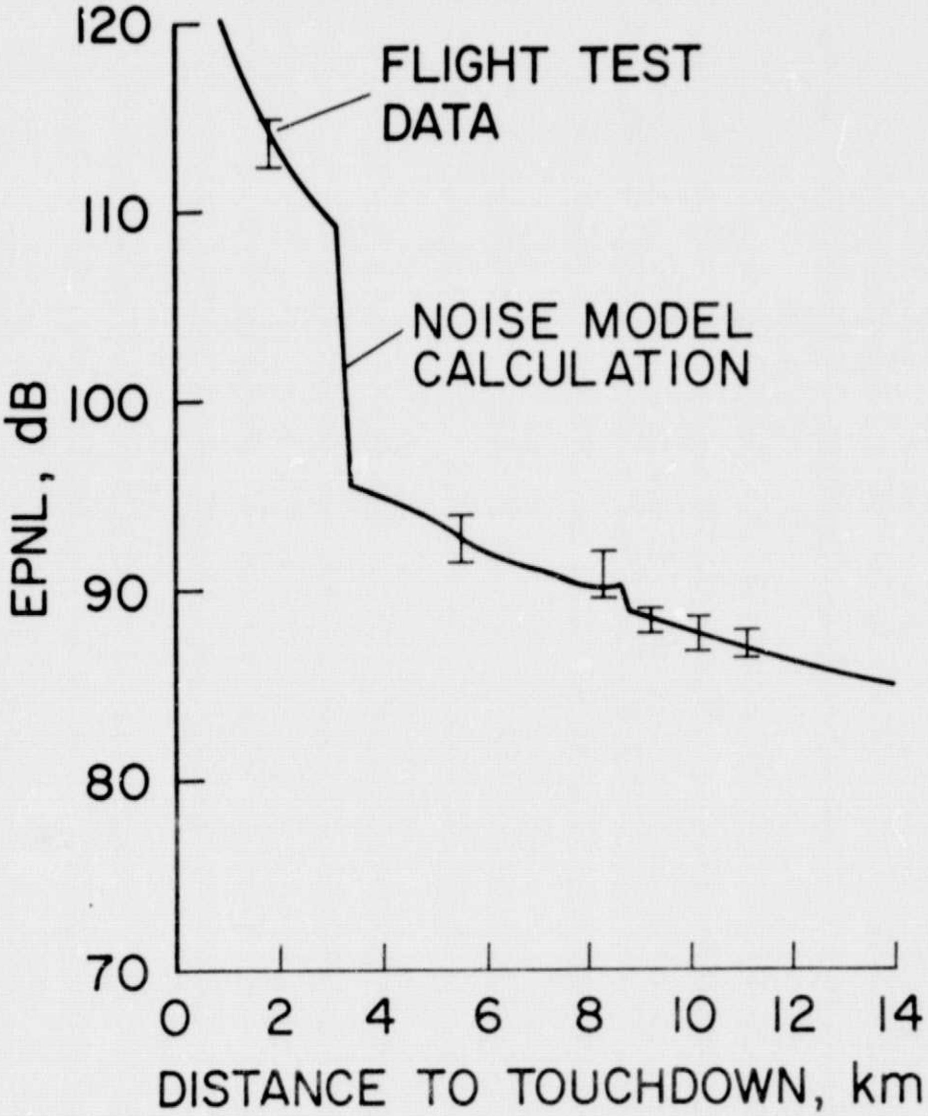
(a) Conventional approach.

Figure 5.- Centerline noise with a 2.5° glide slope.



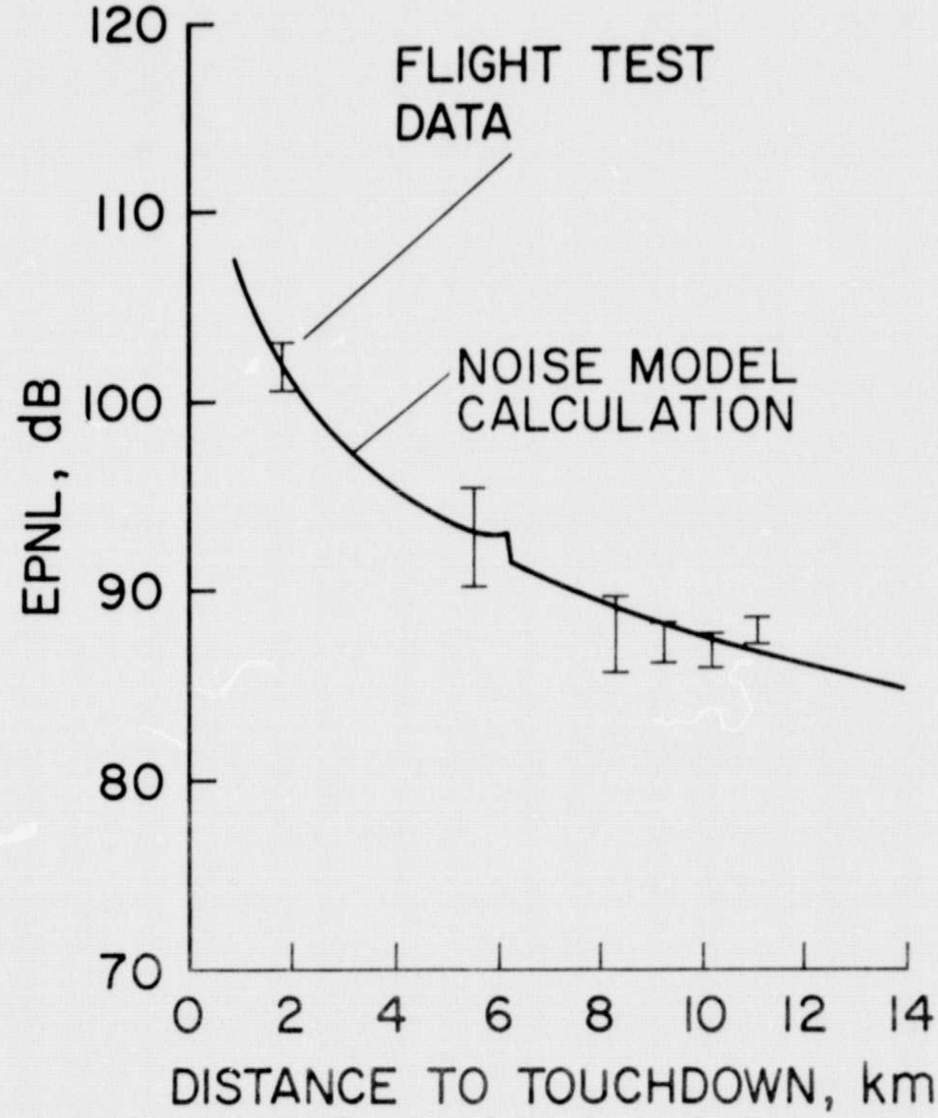
(b) Reduced flap approach.

Figure 5.- Continued.



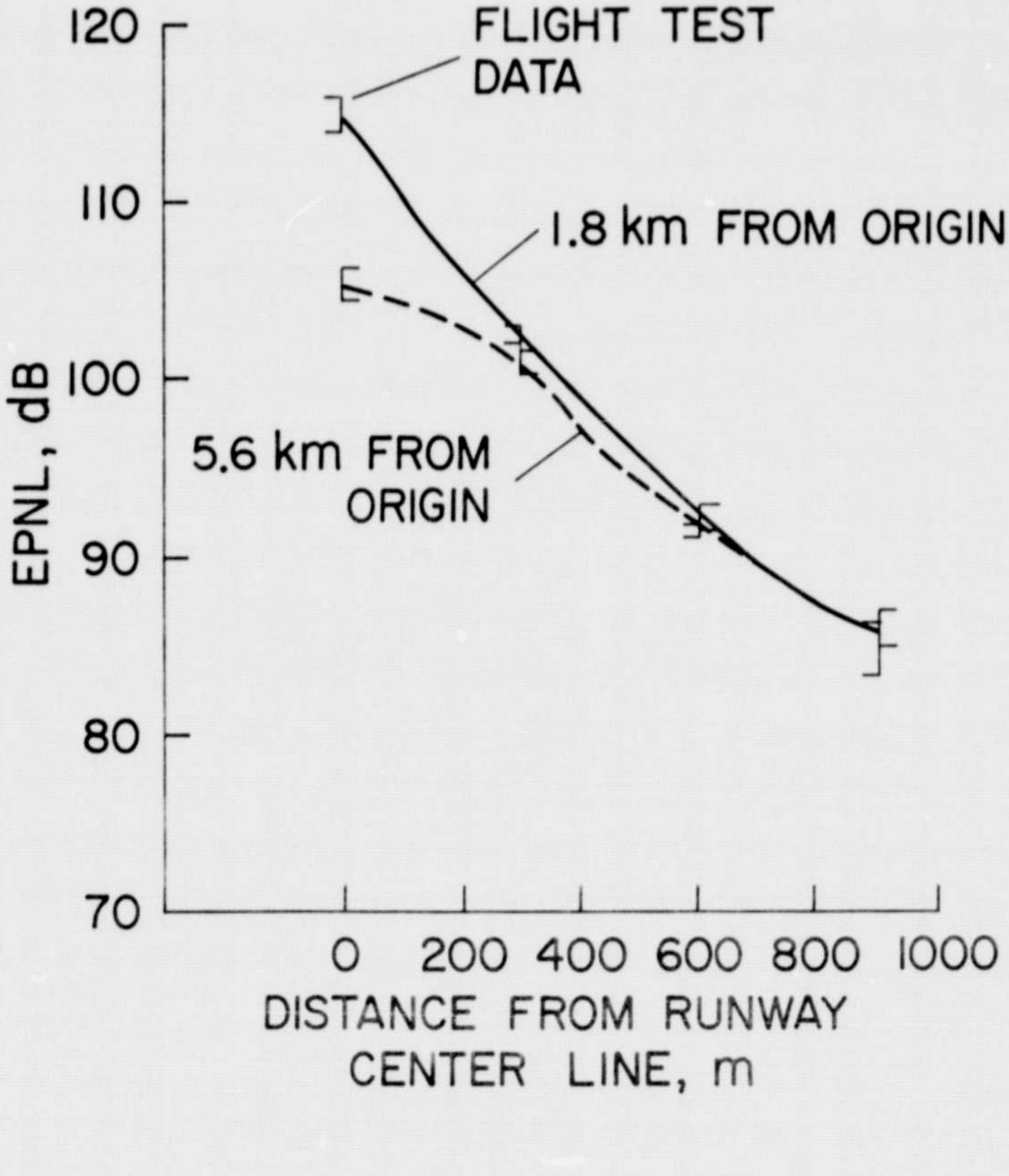
(c) Delayed flap approach.

Figure 5.- Continued.



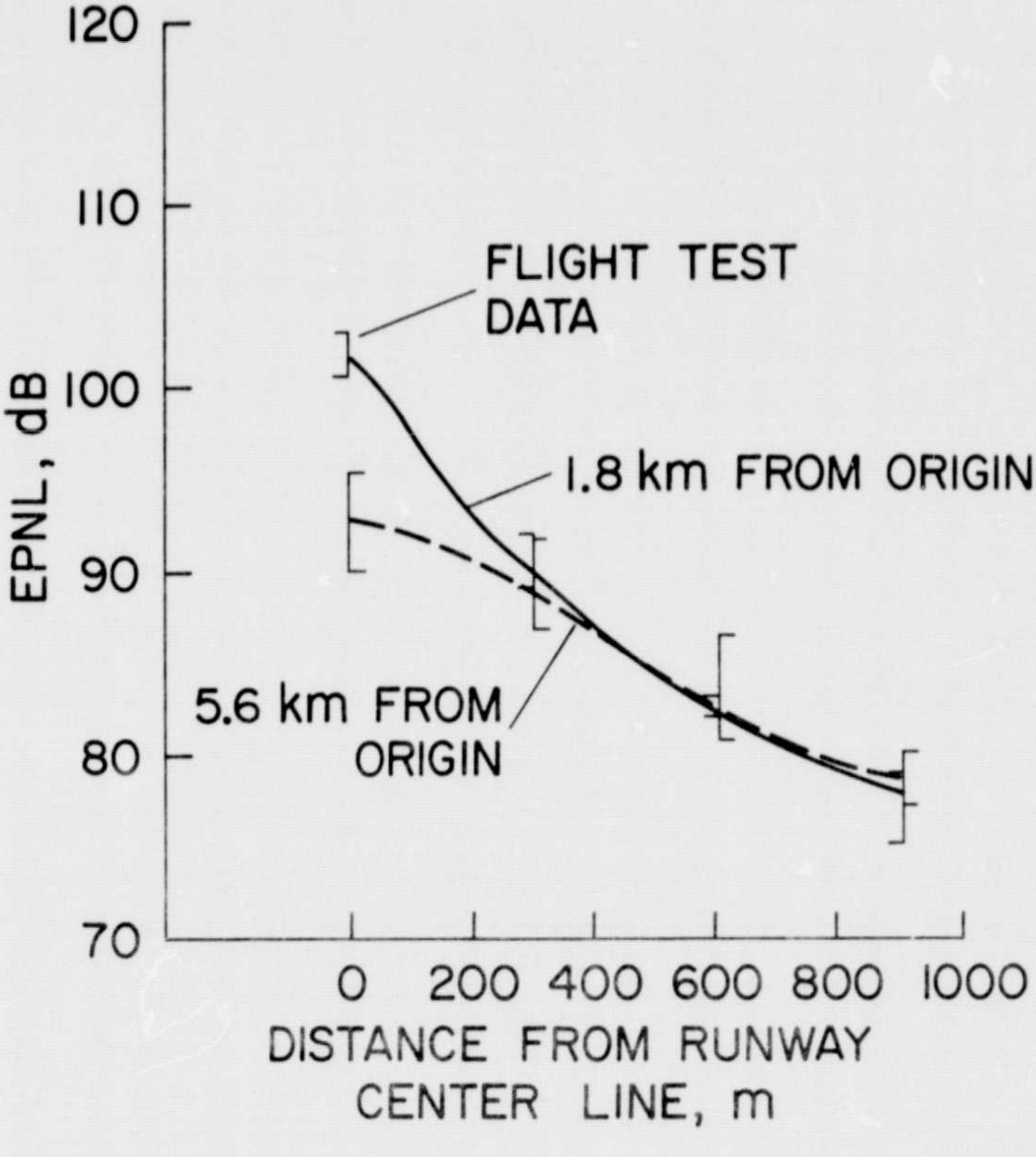
(d) Decelerating approach.

Figure 5.- Concluded.



(a) Conventional approach.

Figure 6.- Sideline noise for the conventional approach at 1.8 km and 5.6 km from the origin.



(b) Decelerating approach

Figure 6.- Concluded.

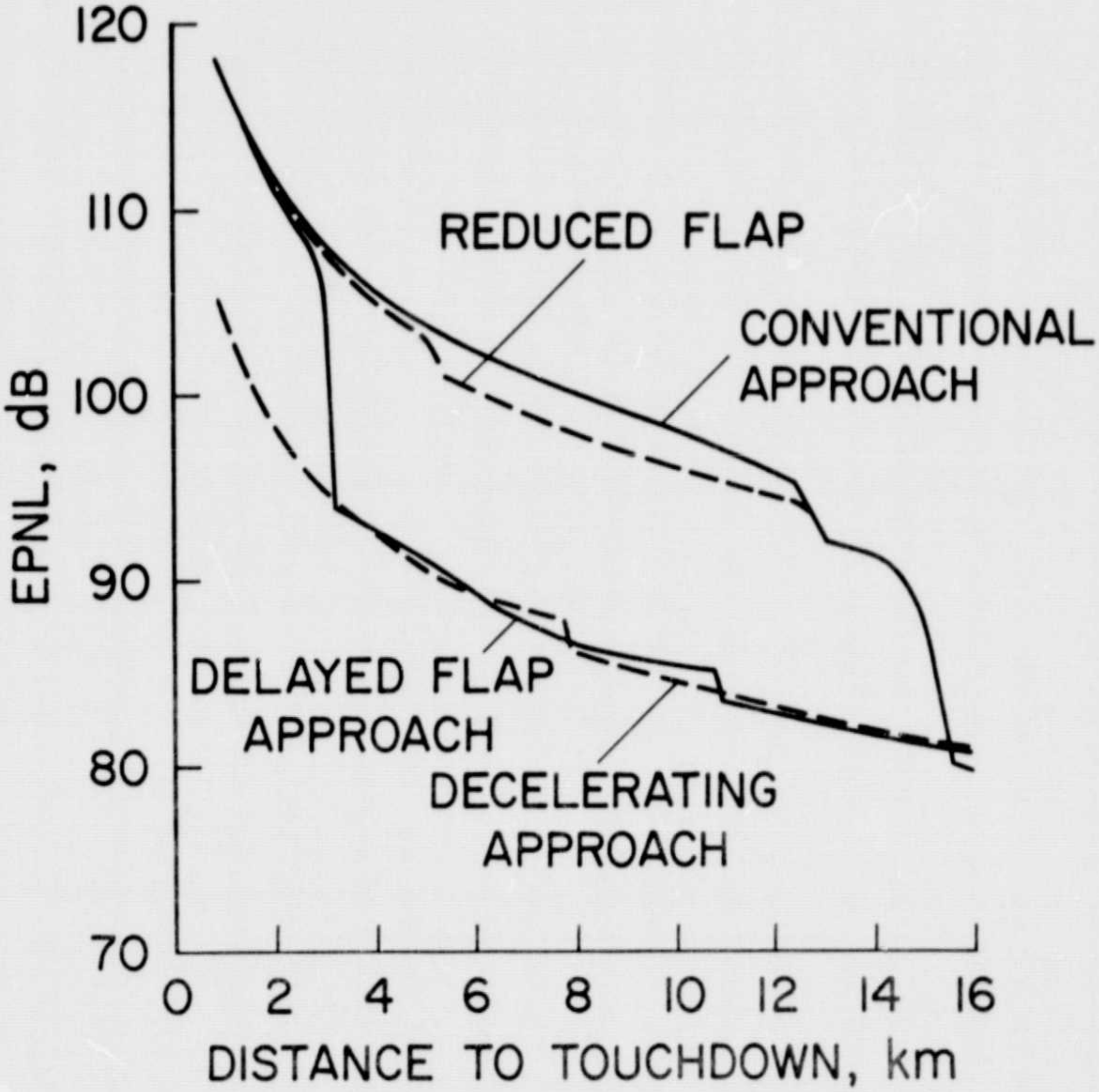


Figure 7.- Centerline noise for a 3° glide slope.

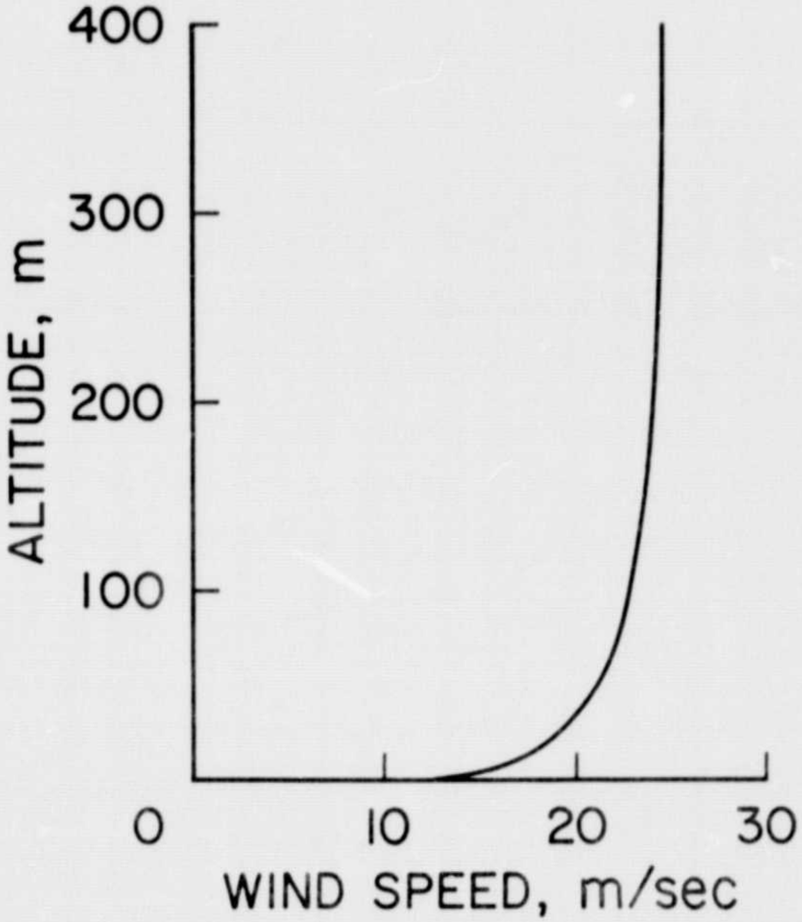


Figure 8.- Simulated wind-speed profile.

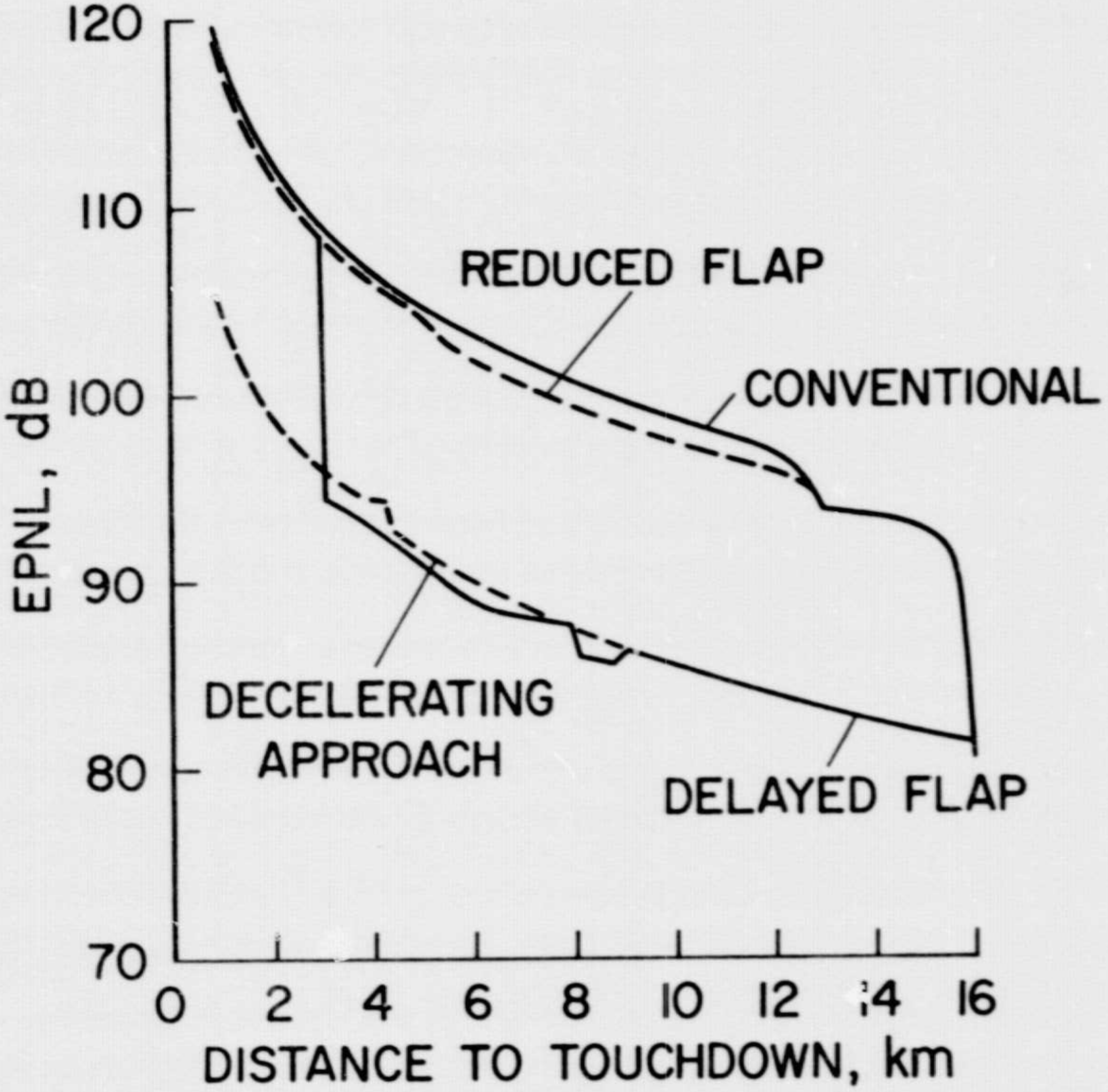


Figure 9.- Centerline noise for a 3° glide slope in a 3σ headwind.

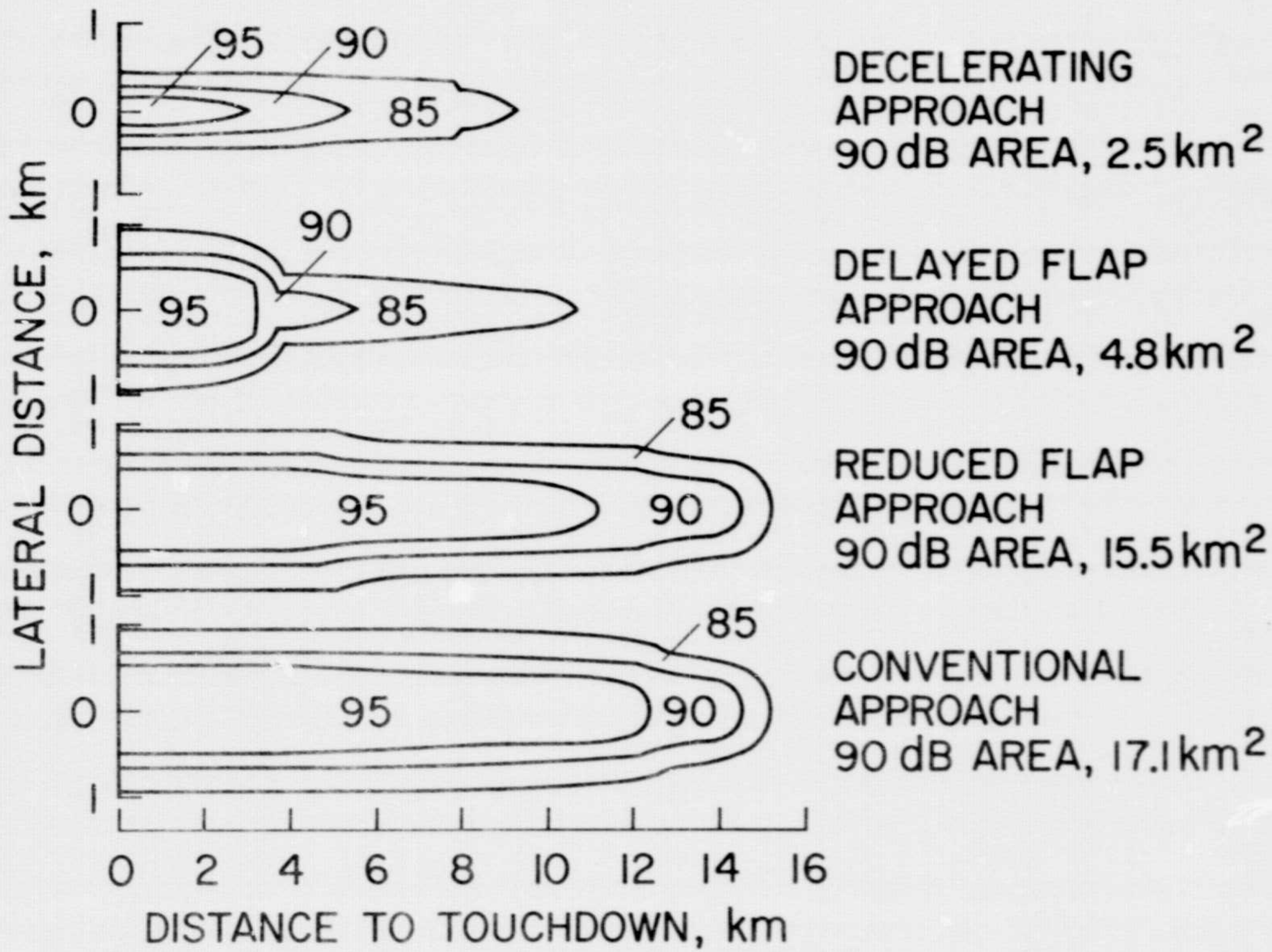


Figure 10.- 3° glide-slope approach noise contours.

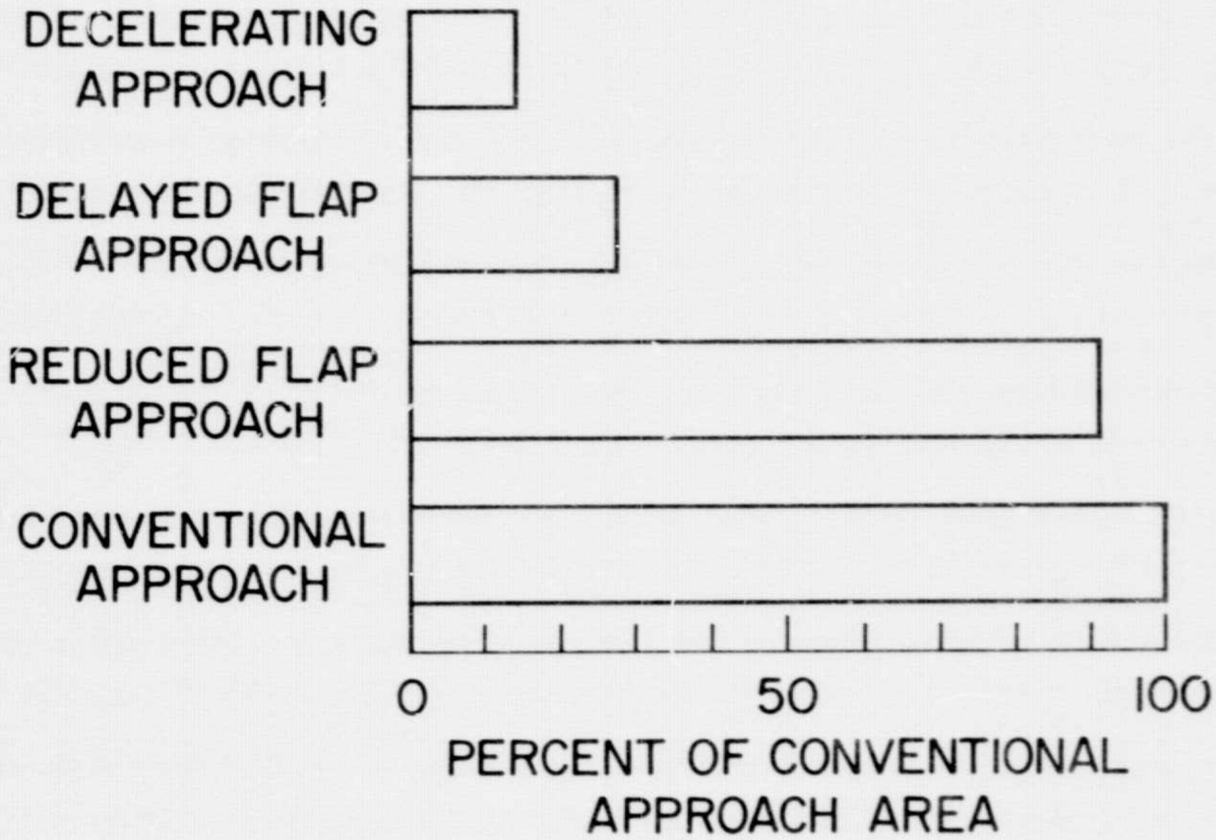


Figure 11.- Normalized comparison of 90 dB contour areas of each approach.